Sensory Z-Slide for Machine Tools

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Summary: Due to the advancements in high speed and high performance cutting, further improvements of machine component design and process monitoring are necessary. For this purpose, new machine components with process monitoring capabilities have to be developed. In this paper, a new spindle carrying Z-slide for a 5-axis machining centre with integrated sensing capabilities for process monitoring is presented. First, the overall system design is described. The sensing capabilities to enable process monitoring are realized by application of a micro-strain gauges network onto the structure of the slide. The optimal sensor positions are computed by application of a special sensor placement algorithm. The prototype of the slide has been built up to investigate the system behaviour. The electronic system of the prototype to realize the signal amplification and the communication via an industrial bus are presented. Furthermore, the results of the system analysis of the prototype are described. Because the sensor amplitudes, which can be monitored by micro-strain gauges on stiff structures are generally small, a method to increase these amplitudes by use of the notch effect with new micro-strain sensors is discussed at the end of the paper. With this method, the signal amplitudes can be increased significantly while the surface of the structure is adapted without degrading the stiffness.

Keywords: Machine, Structure, Optimization, Sensor Integration.

1. Introduction

Recent improvements in production engineering lead to constantly increasing flexibility, productivity, and a higher level of automation. This development results in generally higher demands on machine components and process monitoring strategies. For this reason, components and monitoring strategies have to be enhanced. Monitoring strategies are based on drive- and control-inherent data [1], [2], [3] or on the application of single or multiple sensors [4], [5].

In the collaborative research center ''Gentelligent Components in their Lifecycle'' (CRC653) new "gentelligent®" machine components are investigated to meet these demands. The word "gentelligent®" incorporates the words intelligence and gene. In this context, intelligence is the ability to sense information about the machining conditions, store it and subsequently, process the information by relating it to the information which was previously obtained. Additionally, the system will react on process disturbances by communication with other parts of the manufacturing system. With the word "gene" it is expressed that an evolutionary process is being conducted in the development of these systems: By evolving feedback information, "gentelligent®" systems are therefore able to adapt to the requirements during the product lifecycle.

As a first component, a sensory clamping system was developed. The component senses the process on the workpiece-side and includes a sensor network with which process forces can be reconstructed using special signal processing strategies. With an optimized mechanical design, the sensing capabilities were introduced without degrading the properties of the system behavior. The system was deployed successfully for process monitoring in the individual part production [6, 7].

In a further step, the clamping system was combined with an adaptronic spindle. With the combined sensory machine tool, a robust force-related process monitoring strategy with high sensibility was developed and validated in experimental investigations [8].

Subject of recent works is the development of a novel sensory Z-slide which senses the manufacturing process on the tool side. In this paper, the first results of the development are discussed. First, the overall system design is described. Furthermore, the sensor integration with means of a special sensor placing algorithm as well as the results of the system analysis of the prototype is presented. Finally, a strategy to significantly improve the system behavior by use of the notch effect and novel micro-strain and laser structured strain gauges is discussed.

2. System Design

2.1. System Overview

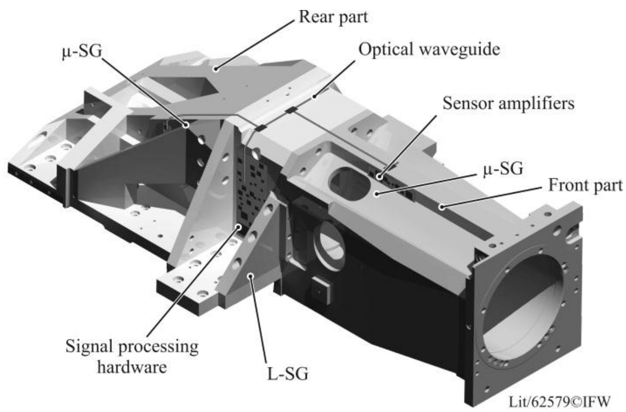

Figure 1. Concept for the sensing Z-slide with light fibre communication and micro strain sensors.

Based on the Z-slide of a high speed machining center (DMG HSC 55 linear) a new light weight Z-slide using integral construction was developed. The resulting system design is depicted in Fig. 1 and briefly described in the following.

In order to reduce weight compared to the original slide which is a cast metal part, the slide is divided into two parts. The front part, in which the spindle is assembled, acts principally as beam which results in a disadvantageous loading condition. Therefore the part is manufactured from high alloy steel, which has a high Young's Modulus to maintain the necessary stiffness. On the contrary, the rear part is supported on four points to the linear guides which leads to a beneficial loading condition. For this reason, it is possible to manufacture this part from aluminum to reduce weight significantly.

The integration of the sensory capability is achieved by measurement of the strains which occur in the structure surfaces due to process loads at the tool centre point (TCP). To measure these strains, novel micro strain gauges (µ-SG), described in detail in [9] and new laser structured gauges (L-SG), described in detail in [10] are used. The sensors are applied on certain points on the structure surface where comparably high strains occur. A total number of nine sensors are integrated. The signal processing hardware for the sensors is fully integrated into the slide. The communication is realized with use of the CAN-Bus. The data is transferred via conventional, or alternatively, via light fibre communication.

2.2. Integration of sensing capability

The main challenge of the system design is the integration of the sensing capability without degrading the stiffness. Components for machine tools are generally overdesigned to achieve maximal stiffness to maintain a high accuracy and stability during the manufacturing process. For this reason, the maximal measurable strains which occur due to process forces are very small. For estimation of the strains in the Z-slide finite element analysis were conducted. Exemplarily, the resulting effective strains for a TCP load of 1 kN in X-direction are illustrated in Fig. 2. As the figure demonstrates, the achievable sensor amplitudes vary significantly. On certain points of the structure, up to 10^{-8} m/m occur.

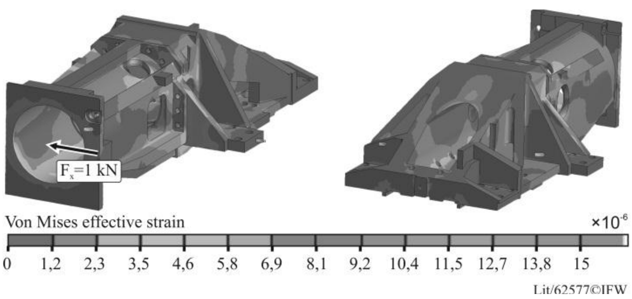

Figure 2. Simulation results for sensor amplitude estimation.

From this results it can be concluded that an optimal sensor placement is crucial to achieve feasible sensor signal amplitudes. For this purpose an algorithm, which was used successfully for the sensor placement in the sensory fixture [6, 7], is used. The optimized sensor positions are depicted in Fig 3.

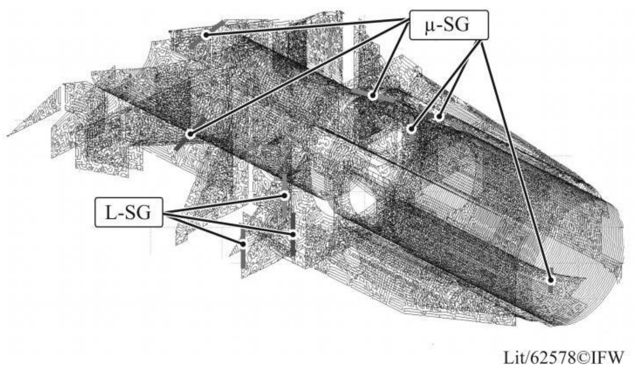

Figure 3. Optimized sensor positions on the Z-slide.

Three micro strain gauges (µ-SG) are attached to the front part of the Z-Slide. Furthermore, three µ-SG are attached to the rear part. Additionally, three laser structured sensors (L-SG) are integrated into an integral key on the side which supports the guiding carriages. The integral keys are especially suitable to integrate L-SG, because they can easily be disassembled for the coating and laser structuring process.

2.3. Communication and Signal Processing

For communication and signal processing, micro-controller based hardware was designed and realized. The system comprises nine controller boxes (one per sensor) which can easily be integrated into the Z-slide (compare figure 4). Because of the small signal amplitudes the controller box has two amplification stages which allow freely programmable amplification factors up to 12,700. With a different resistor setting, even a factor up to 127,000 can be achieved. The sensor signals are measured via a Wheatstone bridge. All bridges are automatically adjusted at start-up by the respective microcontroller. The signals are digitized and sent in time multiplex mode over a CAN-Bus. The multiplexing is necessary to communicate the 9 signals with a sampling rate of 2 kHz and 16 bit resolution. The CAN-Bus can either be realized electrically or optically with fiber optics communication. An interface to realize the fiber optics communication is researched within the CRC653 by the Institute of Transport and Automation Technology.

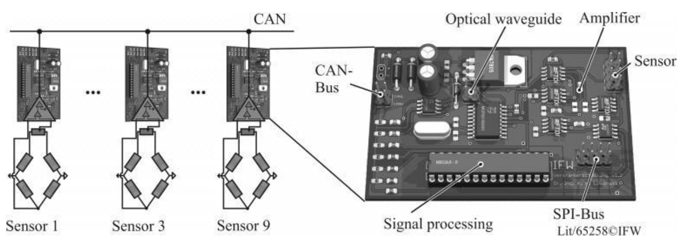

Figure 4. Signal processing and communication of the sensory Z-slide.

3. System analysis of the prototype

To analyze the system behavior, a prototype was built up. The sensory behavior of the prototype was analyzed with dynamic excitation with an electro-dynamic shaker and a reference force sensor. The shaker was attached to TCP of a dummy tool and forces were applied in X-, Y-, and Z-direction with a linear sweep in the frequency range of 0 Hz-1,000 Hz (figure 5).

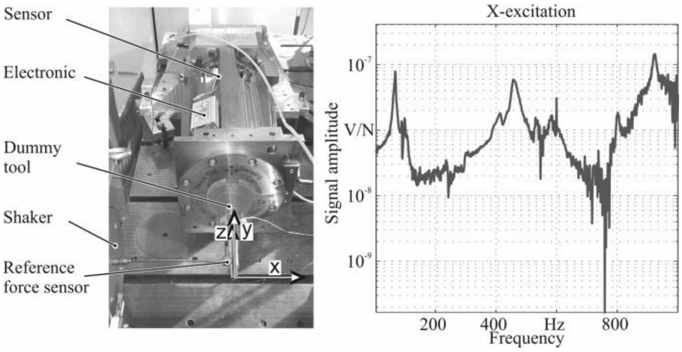

Figure 5. Test setup and frequency response of strain sensor 1 in sensing Z-slide.

The test setup and the transfer behavior of one sensor in X-excitation are depicted in figure 5. A strong noise can be observed in the signals. This is due to the very small amplitudes of about 10^{-8} V/N outside of resonances which is even less than expected from the FE-calculations. A force measurement resolution of up to 10 N can be achieved.

3.1. Method for signal improvement

To raise the signal amplitudes, a concept to increase the measured strains is necessary. This can be achieved by locally adjusting the force flux. This is possible by using the notching mechanism.

When a load is applied on a notched structure, a local stress intensification at the angular point of the notch occurs [11]. From this follows, that by integration of a micro-strain gauge at this location, higher signal amplitudes are measurable compared to a sensor application onto a flat surface. The use of notches is especially advantageous, because the sensors, which are researched within the framework of the CRC653, are extremely small. These sensors permit the use of small notches and consequently lead to less influence on the structural rigidity.

The design of the notch geometry for the laser structured sensor is illustrated in figure 6 and described in the following. As accessibility is of great importance for the application of the sensors, a chamfer with an angle of 120° is chosen as the first parameter. Additionally, the depth of the notch is restricted to 2 mm due to the material thickness of the Z-slide. The notch has a curved ground with a width of *a* to increase strain maxima. The curved ground transits to a linear slope from the respective tangents.

Advantageously, curved surfaces can easily be laser-structured and are therefore suitable for the application of laser-structured sensors. The profile on the notch ground follows a polynomial according to

$$z = \frac{a^{1-p}}{\sqrt{3p}} \cdot \left| x^{p} \right| \qquad (1)$$

To determine the optimal profile parameters to achieve high strain amplitudes in the notch ground, parametrical FE-Simulations were conducted. Within the simulations, the parameters *a* and *p* are varied to compute the maximal amplification factors with the given geometrical boundary conditions

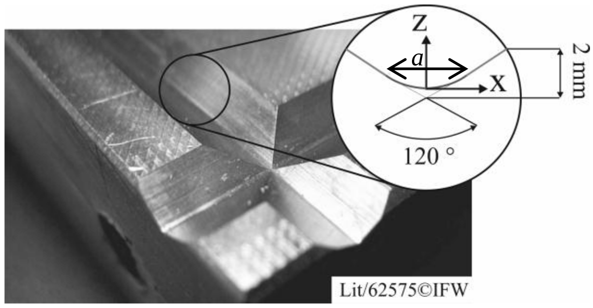

Figure 6. Notch geometry and manufactured sample notches.

As the result of the simulations, the amplification factor of the measurable strains compared to non-notched surface measurement is shown as a function of *a* and *p* in figure 7. As can be seen, decreasing *a* and decreasing *p* lead to a higher strain amplification. These results demonstrate that by application of notches with $a < 0.6$ mm and integrated novel laser structured sensors, a strain amplification over 4 can be achieved. Hence, an improvement of the force resolution from 10 N to less than 3 N is feasible.

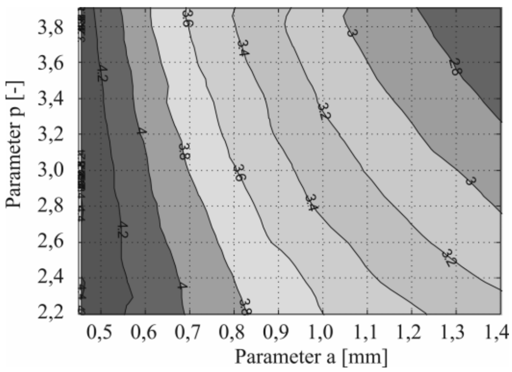

Figure 7. Influence of a and p on strains sensitivity.

4. Conclusion

The present paper shows latest results from the development of a sensing Z-slide for “feeling machine tools”. This research is conducted within the collaborative research centre 653. The design based on finite element simulations is explained. First, the mechanic design and second, the sensory design using a special sensor placement algorithm is presented. A prototypical Z-slide with conventional sensors is realized and the sensing behavior is analyzed experimentally. A force resolution of about 10 N is feasible with the realized system.

A method to increase the signal amplitudes by adjustment of the force flux and micro sensors measuring local strains is shown. An improvement to 3 N is expected when using the notch effect. As a next step the notches will be applied onto the Z-slide and the micro sensors will be applied. The resulting sensory Z-slide will be integrated into the HSC 55 linear machining center for further experimental research.

With combination of two “gentelligent®” components, the first on the tool side and the second on the workpiece side, a system will be built up which is able to communicate among each other and thus, realize the vision of the “feeling machine”.

Acknowledgements

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References

[1] Lapp, C., 2002, Identifikation und Regelung von Bearbeitungskräften an direkt getriebenen Vorschubeinheiten. Dr.-Ing. Dissertation, University of Hannover.

[2] Raibert, M., Craig, J., 1982, Hybrid position/force control of manipulators. In: Brady, M.; Hollerbach, J.; Johnson, T.; Lozano Perez, T.; Mason, M.: Robot Motion: Planning and Control. Cambridge, MIT Press:419-438.

[3] Pritschow, G., Fritz, S., 2004, Rekonstruktion von Prozesskräften bei Direktantrieben unter Verwendung des Ferraris-Sensors. In: Autonome Produktion. Springer, Berlin.

[4] Tönshoff, H. K., Inasaki, I., 2001, Sensors in Manufacturing. Wiley-VCH, ISBN 3-527-29558-5.

[5] Byrne, G., Dornfeld, D., Inasaki, I., Ketteler, G.; König, W.; Teti, R., 1995, Tool Condition Monitoring (TCM) – The Status of Research and Industrial Application. Annals of the CIRP, Manufacturing Technology, 44/2:541-567.

[6] Litwinski, K. M., 2011, Sensorisches Spannsystem zur Überwachung von Zerspanprozessen in der Einzelteilfertigung. Dr.-Ing. Dissertation, Leibniz Universität Hannover.

[7] Denkena B., Mohring, H-C, Litwinski K.M., 2008, Design of dynamic multi sensor systems. Production Engineering and Research, 3:327–331.

[8] Möhring, H.-C., Litwinski, K. M., Gümmer, O., 2010, Process monitoring with sensory machine tool components. CIRP Annals – Manufacturing Technology, 59/1:383-386.

[9] Düsing, J. F., Suttmann, O., Klug, U., Kling, R., Litwinski, K., Möhring, H.-C., Denkena, B., 2010, Neue Ansätze für die Produktionstechnik durch bauteilinhärente Sensorik. Produktion von Leiterplatten und Systemen, 12:2887-2892.

[10] Griesbach, T., Wurz, M.C., Rissing, L., 2011, Application of Sacrificial Layers for the Modular Micro Sensor Fabrication on a Flexible Polymer Substrate, Sensor+Test Conference 2011, Sensor Proceedings.

[11] Neuber, Heinz, 1985, Kerbspannungslehre, Springer Verlag, Berlin, Heidelberg.